공학석사 학위논문

Adaptive Random Back-Off in Timeslot for Mitigating Collisions of TSCH Networks

TSCH 네트워크에서 충돌을 완화하기 위한 Timeslot 내 적응적 랜덤 Back-Off 전송

2020년 8월

서울대학교 대학원

전기·정보공학부

박 정 준

공학석사 학위논문

Adaptive Random Back-Off in Timeslot for Mitigating Collisions of TSCH Networks

TSCH 네트워크에서 충돌을 완화하기 위한 Timeslot 내 적응적 랜덤 Back-Off 전송

2020년 8월

서울대학교 대학원

전기·정보공학부

박 정 준

Adaptive Random Back-Off in Timeslot for Mitigating Collisions of TSCH Networks

지도 교수 박 세 웅

이 논문을 공학석사 학위논문으로 제출함

2020년 7월

서울대학교 대학원

전기·정보공학부

박 정 준

박정준의 공학석사 학위 논문을 인준함

2020년 6월

위 원 장: ____________________________

부위원장: ____________________________

위　　원: ____________________________

Abstract

Recently, as the market of Internet of Things (IoT) has been rapidly extending and developing, the research focusing on low-power wireless sensor networks has been actively ongoing. In particular, for the satisfaction of IoT requirements, many studies have been conducted using IEEE 802.15.4 TSCH (Time-Slotted Channel Hopping) based networks with characteristics of high reliability and low-power. Transmitter and receiver using TSCH can exchange the data through time-synchronized communication using timeslot. However, if multiple users transmit the packets on the same timeslot and channel in the TSCH network, severe data collisions may occur. In this paper, we propose Random Back-Off TSCH (RBO-TSCH) which helps to mitigate the collisions by proceeding a random back-off in the timeslot before transmission. In addition, to reduce the energy consumption of RBO-TSCH, we propose *receiver-triggered* RBO-TSCH which can adaptively control the number of a random back-off set at the receiver side. To verify this, we conduct extensive experiments and evaluate the RBO-TSCH and *receiver-triggered* RBO-TSCH. Compared to TSCH, we demonstrate that RBO-TSCH and *receiver-triggered* RBO-TSCH demonstrate achieve up to 3.8 times higher reliability and have higher stability against collision in both link layer and routing layer.

keywords: IEEE 802.15.4, TSCH, Random Back-Off, CCA, Wireless Sensor Networks.

student number: 2018-25692

Contents

List of Tables

List of Figures

Chapter 1

Introduction

Internet of Things (IoT) technology has drawn much attention recently, and the rapid growth of massive scale IoT applications leads to large usage in many areas such as smart homes, smart cities, and smart health care [1–3]. As a result, high transmission reliability and low-power consumption have been required in large scale IoT application areas and become an important issue. To satisfy the requirements, IEEE 802.15.4 TSCH (Time-Slotted Channel Hopping) based wireless sensor networks have been frequently used in recent years.

In TSCH, a transmitter and receiver exchange a packet by using a time-slotted manner and communicate with each other by hopping multiple channels. The transmitter and receiver make an attempt in specific timeslots and channels to communicate with each other. Therefore, using TSCH could have a low radio duty-cycle through the characteristic of time synchronization. Since the transmitter and receiver only turn on the radio at the timeslot required for transmission and turn off the radio at the rest of the time. Also, using TSCH has high transmission reliability since it is robust from external interference by operating the channel hopping mechanism. Although using the TSCH has advantages of low power consumption and high reliability, it can cause a problem in the case of applying the massive scale IoT application. According to a mechanism of TSCH, the transmitters use channel clear assessment (CCA) for collision avoidance. However, if multiple transmissions occur at the same timeslot and channel, an intra-network collision avoidance using CCA becomes meaningless, and all of the data in the timeslot crash with each other. Even though CCA should be operated in the packet duration of another transmitter for the successful collision avoidance, since the starting point of CCA of transmitters is closely aligned due to the time-synchronized characteristic in the TSCH.

In this paper, we propose random back-off TSCH (RBO-TSCH) to mitigate the problems of TSCH operation caused by time synchronization. Each transmitter transmits the packet after a randomly selected delay in the RBO-TSCH. Therefore, the RBO-TSCH is strongly helpful to mitigate the collisions. However, the RBO-TSCH consumes more energy than TSCH since the receiver using the RBO-TSCH turns on radio longer to guarantee the packet transmitted through random back-off in the timeslot. To reduce the energy consumption of the RBO-TSCH, we also design and implement *receiver-triggered* RBO-TSCH. For the performance evaluation, several experiments are conducted in a real testbed of IoT-LAB [4].

The main contributions of this paper are threefold.

- We point out the CCA operation for collision avoidance in the TSCH is not helpful in the intra-network collision resolution. This means the TSCH can cause severe degradation of reliability and a lot of energy consumption when it is applied to the massive scale IoT application scenario.
- We design and implement the RBO-TSCH, a modified TSCH operation to randomly back-off within the timeslot, to mitigate severe collisions which are inevitable due to CCA operation in TSCH. In addition, we also propose a *receiver-triggered* RBO-TSCH that checks the presence of collisions and adaptively adjusts the range of transmitter's random delay at the receiver side to reduce the energy consumption due to becoming longer Rx listening time of RBO-TSCH.
- We demonstrate that RBO-TSCH and *receiver-triggered* RBO-TSCH have up to

3.8 times higher reliability than TSCH in higher traffic scenario by implementing on commodity 32-bit ARM Cortex-M3 microcontroller (STM32F103REY) and IEEE 802.15.4 radio chip (AT86RF231). Moreover, we address that RBO-TSCH and *receiver-triggered* RBO-TSCH can achieve a more robust network against the collision than TSCH.

The remainder of this paper is organized as follows. §2 represents the necessary background on TSCH and the problem statement of TSCH operation. §3 addresses the design of the RBO-TSCH operation and deals with the drawback of RBO-TSCH. §4 discusses the design of *receiver-triggered* RBO-TSCH. §5 details implementation aspects and discusses experimental evaluations of RBO-TSCH and *receiver-triggered* RBO-TSCH. In §6, we conclude this paper.

Chapter 2

Backgrond

2.1 Time-Slotted Channel Hopping (TSCH)

TSCH is a time-synchronous MAC operation which is specified in the IEEE 802.15.4 standard [5]. Basically, the operation period of the TSCH network is divided into multiple timeslots, and TSCH operates on a particular channel at each timeslot. Figure 2.1 shows an example of the TSCH schedule and tree topology for data collecting. The basic scheduling unit in TSCH is a cell that contains specific timeslot and channel offset. For example, when the transmitter and receiver communicate in the cell as represented in Figure 2.1, they communicate on the pre-scheduled particular cell and exchange a single frame and acknowledgement (ACK) within the timeslot. The nodes should be

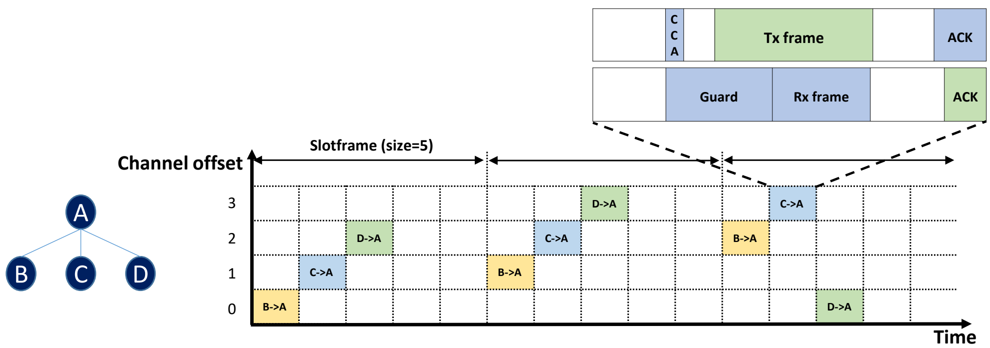


Figure 2.1: An example of TSCH schedule and tree topology for data collecting.

synchronized by timing information from their timesource. Node A is the timesource of node B, C, and D in the example of Figure 2.1. Each node is periodically scheduled and this period is determined by the size of the slotframe. In each slotframe, each node is always assigned at the same time offset, while the channel changes following the channel hopping mechanism. Compared to asynchronous MAC protocols [6–8], TSCH can reduce the redundant transmissions that are required for matching up the rendezvous and can achieve the robustness from external interference by using the channel hopping mechanism. For this reason, we can achieve low-power consumption and high reliability by using the TSCH.

2.2 Problem Statement

In large scale IoT network, a node cannot transmit a packet to a destination node through a single-hop since the distance between transmitter and receiver (destination node) is so far away. And also, since the nodes only have constrained resources such as low transmission power, it is impossible to transmit the packet to a destination in a direct way. For this reason, each node should transmit its packets via multi-hop transmission. A routing layer is needed to transmit the packet through multi-hop transmission. Thus, we use a routing protocol for low-power and lossy networks (RPL) [9]. RPL is a universal routing protocol in wireless sensor networks and uses expected transmission count (ETX) based objective function as a default, so it configures the routing path by link reliability. In addition, *Orchestra* [10], RPL-based scheduler for TSCH, is used to schedule the nodes into the specific cell. The Figure 2.2 shows an example of receiver-based scheduling in *Orchestra*. In the receiver-based scheduling in *Orchestra*, each node acquires the chance of Rx on each timeslot and adjacent nodes can acquire the Tx chance as described in resource scheduling of Figure 2.2. For example, if node A acquires the Rx chance on the first timeslot in each slotframe, the adjacent nodes can get the Tx chance in the same cell. In this case, multiple transmitters compete with

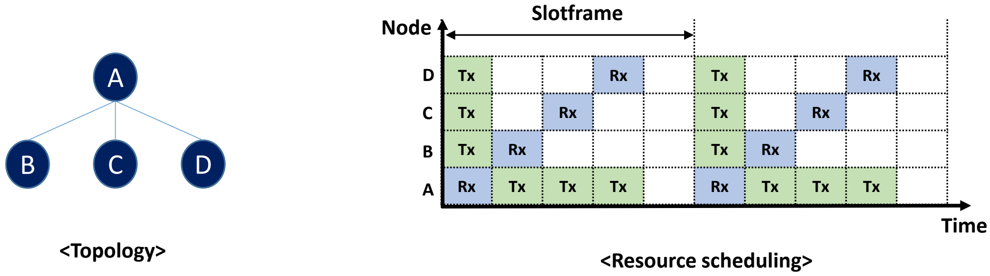
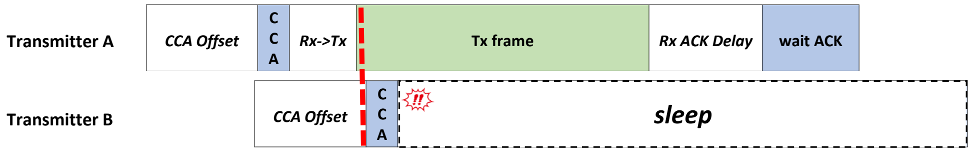


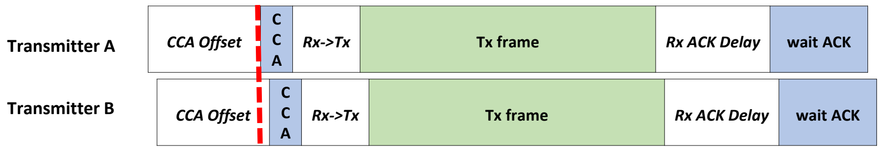
Figure 2.2: An example of receiver-based scheduling in *Orchestra*.

each other to transmit their packet to node A. Therefore, the node A can be suffered from collision by several transmitters. Although this problem may be resolved by collision avoidance through CCA, however, the problem still exists in the TSCH due to its CCA operation.

Since TSCH communicates in a time-slotted manner, it requires elaborate time synchronization between transmitter and receiver. For this reason, if there are multiple transmitters to transmit the data, the CCA operation for collision avoidance becomes meaningless in an intra-network. Figure 2.3 shows the structure of transmitting timeslot in IEEE 802.15.4 TSCH. In Figure 2.3, there is a transition time between the CCA operation and the Tx frame. The transition time depends on hardware capacity. In Figure 2.3(a), to avoid the collision through CCA, **Transmitter B** should operate the CCA during packet transmission duration of **Transmitter A**. However, collision avoidance is impossible in elaborately time-synchronized TSCH since starting points of TSCH operations of multiple transmitters are closely aligned as represented in Figure 2.3(b). Operating their CCA of each transmitter at almost the same time makes intra-network collision avoidance using CCA ineffective. Thus, in a wireless sensor network environment with high transmission volumes, TSCH increases the probability of data collisions, which significantly reduces transmission reliability. To improve this, we propose random back-off TSCH (RBO-TSCH) which applies random back-off into the timeslot of TSCH for detecting the packets of another transmitter by using the CCA.



(a) CCA operation for collision avoidance in TSCH



(b) General CCA operation in TSCH

Figure 2.3: The structure of transmitting timeslot and multiple transmissions in IEEE 802.15.4 TSCH.

Chapter 3

Random Back-Off TSCH (RBO-TSCH)

3.1 Design of RBO-TSCH

In Legacy TSCH, when the volume of traffic is augmented, severe collisions occur since it cannot use CCA operation for collision avoidance due to the characteristic of time-synchronized communication. To resolve this, we propose RBO-TSCH which is the MAC operation to mitigate the collisions by proceeding a random back-off before transmission in the timeslot. However, if the transmitter executes its CCA operation between CCA and transition time of another transmitter as described in Figure 2.3(b), the collision problem still may exist even though the transmitter uses a random back-off procedure. Thus, if the back-off proceeds vaguely and randomly without specific rules in operating random back-off within timeslot duration, it is not effective in resolving the collision. Although proceeding a random back-off before transmission, since the same problem such as Figure 2.3(b) may occur frequently. Therefore, the RBO-TSCH proceeds back-off within timeslot with its own rules.

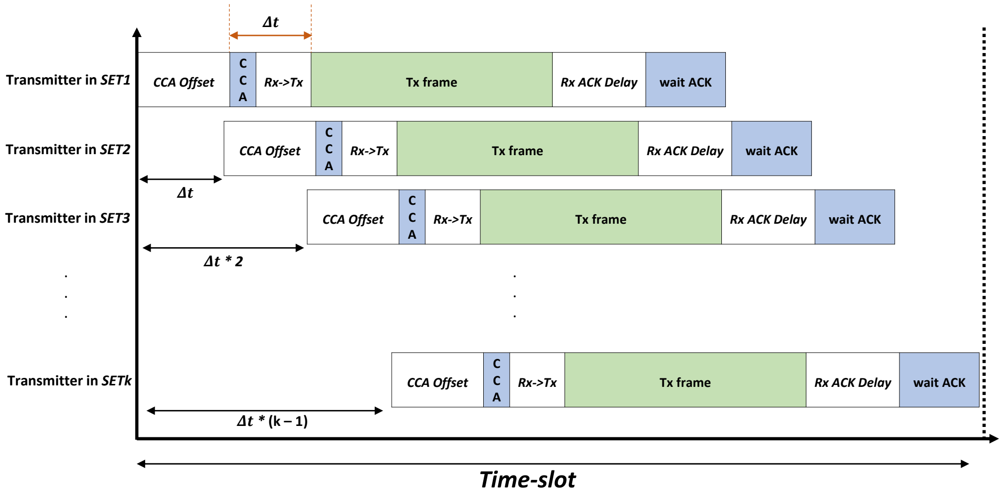


Figure 3.1: Configuration of back-off delay.

3.2 Consideration of RBO-TSCH

In RBO-TSCH, there are two specific rules in applying random back-off in timeslot before transmitting the packet: **(1)** MAC operation of RBO-TSCH should be configured so that the CCA can detect Tx frame from other transmitters. **(2)** Clock drift correction process in transmitter side should modify clock drift by considering random back-off of the transmitter. The detailed operations about the considerations are followed the below subsection.

3.2.1 RBO SET

To guarantee the collision avoidance through CCA from another traffic, we determine k back-off sets in RBO-TSCH. In RBO-TSCH, the k can be dependent on hardware capability, and only one set is chosen randomly among the k sets. After choosing the one set randomly, TSCH operation starts after the back-off delay of that set like in Figure 3.1. A Δ t denotes duration between the start of CCA and right before the packet transmission. If the back-off delay difference of the adjacent sets is smaller than Δt, CCA cannot detect another packet as mentioned in Section 3.1. This problem causes severe collisions and loss of reliability. For this reason, we configure the RBO SET to operate the randomly selected back-off set k after $\Delta t \cdot (k\text{-}1)$.

3.2.2 Clock Drift Correction

Since TSCH transmits the packet in a time-slotted manner, time synchronization between transmitter and receiver is surely significant. For this, transmitter corrects a clock drift through timing information in ACK from a timesource (only the case of upward traffic transmission). If the transmitter selects the back-off set k, it receives the timing information including the back-off delay of set k ($\Delta t \cdot (k\text{-}1)$). For the estimation of real clock drift, the transmitter excludes the back-off delay from timing information in ACK of the timesource. As a consequence, the real clock drift which should be corrected is calculated as an equation below.

Real clock drift for clock drift correction

= (*Timing information in ACK*) – (*Back-off delay of set k*)

= (*Clock drift* + *Back-off delay of set k*) – (*Back-off delay of set k*)

= Clock drift

3.3 Weakness of RBO-TSCH

In the case of using RBO-TSCH, as the receiver does not know which back-off set is applied to the packet transmission from the transmitter, the receiver should turn on the radio longer than TSCH to guarantee the packet applied to random back-off. For example, the receiver in TSCH should turn on the radio for guard interval and receiving the Tx frame as described in Figure 3.2. If there is no traffic, the receiver waits for the Tx frame until the duration of the second guard interval and turns the radio off. In the case of TSCH, the receiver turns on the radio during at most the duration of the Tx frame according to the presence of the traffic. However, when there is traffic heading

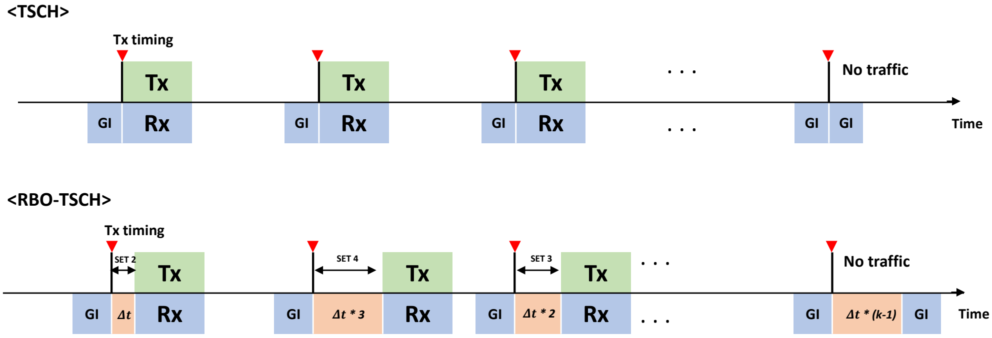


Figure 3.2: Radio-on time comparison of receiver in TSCH and RBO-TSCH.

to the receiver, the receiver in RBO-TSCH consumes more energy since it turns on the radio longer than TSCH to receive the packet applied to random back-off. Although there is no traffic, the receiver should turn on the radio to wait for the maximum back-off delay packet of the transmitter. Since the Tx frame applied to the last RBO SET may arrive in the receiver, the receiver still wastes more energy than the receiver of TSCH as shown in Figure 3.2.

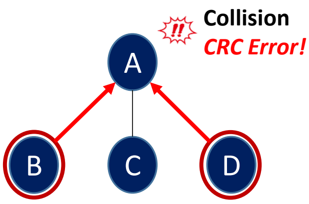
Actually, when the traffic load is relatively low, the probability of collision also low. Thus, although the RBO-TSCH operation may not be needed in lower-traffic cases, it is used in lower-traffic and causes higher energy consumption. To reduce the energy consumption, we propose *receiver-triggered* RBO-TSCH which can adaptively select the number of the random back-off sets (RBO SET) at the receiver side.

Chapter 4

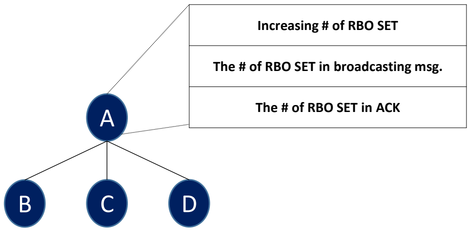
Receiver-triggered RBO-TSCH

4.1 Design of *Receiver-Triggered* RBO-TSCH

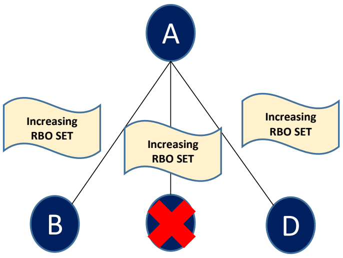
We propose the RBO-TSCH to mitigate the collisions in TSCH networks. However, RBO-TSCH may be unnecessary in a lower collision situation since it could waste redundant energy from a random back-off procedure even though there is no collision. In the lower collision situation, in other words, the operation of RBO-TSCH may cause the augmenting of the radio duty cycle. In consequence, we design the RBO-TSCH is used for higher collision by adaptively increasing the number of RBO SET (described in section 3.2.1) and used for lower collision by decreasing the number of RBO SET adaptively. In *receiver-triggered* RBO-TSCH, the receiver can detect the collision and adaptively control the number of RBO SET. When the receiver detects the collision, it immediately increases the RBO SET size in *receiver-triggered* RBO-TSCH. Increasing RBO SET is an aggressive operation since it increases RBO SET as soon as detecting any collision. On the other hand, decreasing RBO SET is a conservative operation since it decreases RBO SET size by considering the presence of collision in the receiver side. To explain it better, the process of *receiver-triggered* RBO-TSCH is represented in the following section.



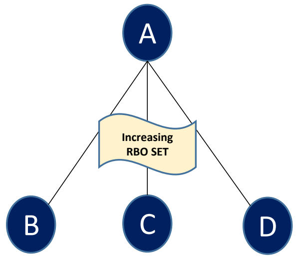
(a) Detecting collision in receiver node A



(b) Increasing the number of RBO SET



(c) Sending command via broadcasting message



(d) Sending command via ACK

Figure 4.1: An example of increasing RBO SET operation.

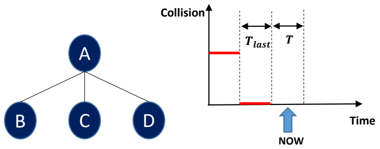
4.1.1 Operation of Increasing RBO SET

To increase the number of RBO SET, the receiver detects whether there is any collision when it receives the packet from multiple transmitters. When the receiver detects the collision, it uses a cyclic redundancy check (CRC) information from its radio layer. If the CRC information is broken, it infers that the collision has occurred. Exactly, we indirectly use the CRC information since there is no direct way to detect the existence of collision on the receiver side. The meaning that CRC information is broken implies packet collision. Since the operation of increasing RBO SET should be aggressively triggered for maintaining transmission reliability, using CRC information is not a problem to decide a collision.

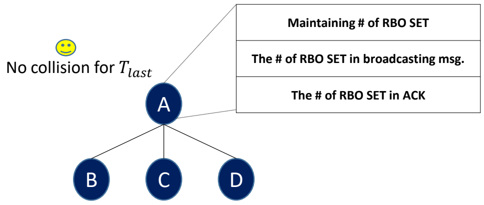
For example, the receiver receives the packet from multiple transmitters in Figure 4.1(a). If the CRC information is broken, the receiver adaptively increases the number of RBO SET by 1 on immediately as shown in Figure 4.1(b). After that, the receiver generates a broadcasting message included the size of RBO SET and broadcasts it to the network as described in Figure 4.1(c). To guarantee the transmitters which do not receive the broadcasting message, the receiver also generates enhanced ACK with the size of RBO SET and transmits it to transmitters when they exchange the unicast message as shown in Figure 4.1(d). The size of RBO SET in the broadcasting message and enhanced ACK is maintained until the receiver increases or decreases the size of RBO SET. This operation has negligible overhead since it uses reserved bits in injecting the RBO SET size into the broadcasting message and enhanced ACK.

4.1.2 Operation of Decreasing RBO SET

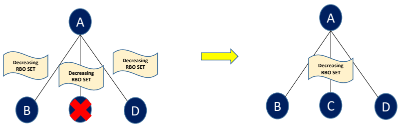
Decreasing the RBO SET requires attention since this operation affects the transmission reliability. For example, if the number of RBO SET is decreased even though there is a high collision situation, the collision would still exist, and reliability would be decreased. Thus, the receiver should estimate the collision history to decide the possibility of collision in an indirect way. Figure 4.2 exemplifies the operation of decreasing RBO SET. The receiver measures the collision history by checking whether the CRC is broken or not for time T_{last} as shown in Figure 4.2(a). We set up *T* to observe the collision for a sufficient amount of time. When the *receiver-triggered* RBO-TSCH uses the RBO SET larger than RBO SET 1 (using back-off set 1), the receiver estimates its collision history periodically. If the collision occurs in last time T_{last}, RBO-TSCH increases the number of RBO SET by 1. Otherwise, the receiver generates a broadcasting message and enhanced ACK with the decreased size of RBO SET by 1 and transmits them to the network as described in Figure 4.2(b) and (c). The receiver does not decrease the RBO SET immediately and waits for T_{wait} since it has to wait until all the transmitters decrease the RBO SET. After waiting for T_{wait}, if there is no CRC error, the receiver decreases the number of RBO SET to reduce energy consumption as shown in Figure 4.2(d).



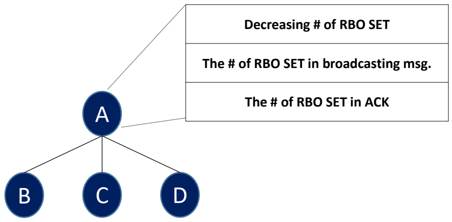
(a) Checking collision history for T_{last}



(b) Generating command with decreasing size of RBO SET



(c) Sending command via broadcasting message and ACK



(d) Decreasing the number of RBO SET

Figure 4.2: An example of decreasing RBO SET operation.

Chapter 5

Performance Evaluation

5.1 Experimental Setting

In this paper, we evaluate the performance of RBO-TSCH and *receiver-triggered* RBO-TSCH on real-world testbed in IoT-LAB of Strasbourg, France. IoT-LAB has state-of-the-art IoT devices with a 32-bit ARM Cortex-M3 microcontroller (STM32F103REY) and an AT86RF231 IEEE 802.15.4 radio chip [4]. 32 nodes are used in the experiments and deployed with 2 meters distance in the building as described in Figure 5.1. Every node (except for node 1) transmits the packets to node 1 with various traffic loads. The details about experimental settings are represented in Table 5.1.

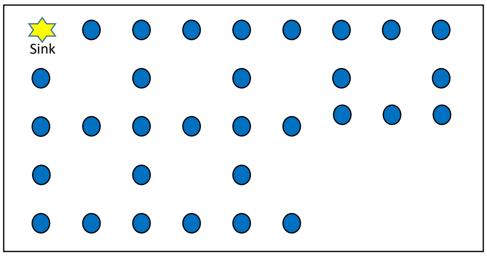


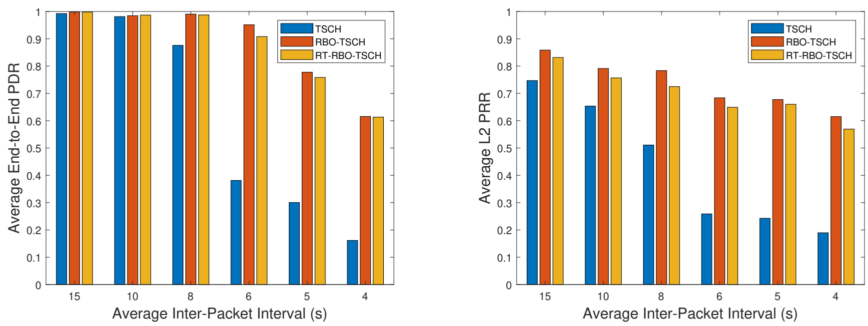
Figure 5.1: Topology of experiment with 32 nodes.

Table 5.1: Experimental settings in IoT-LAB testbed

Operating system	*Contiki NG*
Environment	*IoT-LAB (Strasbourg)*
Scale	*32 nodes*
Tx power	*-17 dBm*
Channel	*15, 20, 25, 26*
DIO filtering	*-87 dBm*
Size of RBO SET	*up to 4*
Running time	*30 min.*
Metrics	*Reliability, energy consumption, and network stability*

5.2 Communication Reliability

To verify the performance gain of RBO-TSCH compared to TSCH, we evaluate the average end-to-end packet delivery ratio and link reliability which is the link layer packet reception ratio (PRR). The traffic load is set by changing the average inter-packet interval (IPI). Figure 5.2 shows the average end-to-end reliability and link reliability according to average IPI. As average IPI decreases in both graphs, the gap between TSCH and RBO-TSCH is larger. Although collision probability increases in increasing traffic load, RBO-TSCH can overcome the collision effectively. As a result, RBO-TSCH has about 3.8 times higher end-to-end reliability and about 3.2 times higher link reliability than TSCH. Receiver-triggered RBO-TSCH (RT-RBO-TSCH)



(a) End-to-end reliability (b) Link reliability

Figure 5.2: The evaluation of communication reliability.

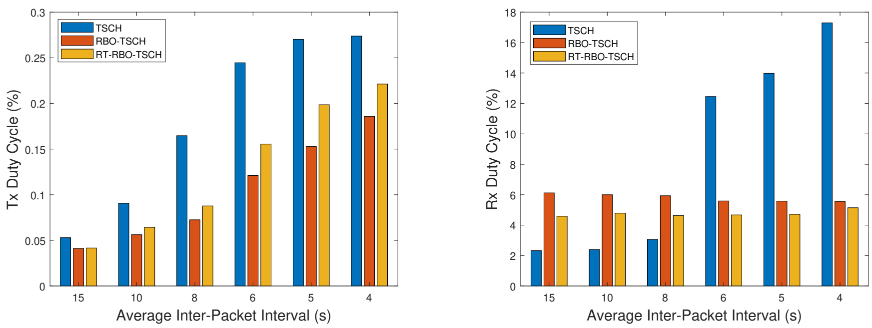
also outperforms than TSCH, however, it is slightly lower than RBO-TSCH since it adaptively controls the size of RBO SET by referring to the presence of the collision. Although RT-RBO-TSCH has some reliability loss than RBO-TSCH, which is a reasonable result for reducing energy consumption.

5.3 Radio Duty Cycle

As we mentioned in Section 3.3, in the case of using RBO-TSCH, the receiver should turn the radio on longer than TSCH. Figure 5.3 shows the Tx radio duty cycle and Rx radio duty cycle.

In the Tx radio duty cycle graph, when average IPI decreases, the Tx duty cycle of TSCH, RBO-TSCH, and RT-RBO-TSCH increases due to augmenting traffic load. In RBO-TSCH, each node can effectively detect another Tx frame through CCA by using a back-off procedure, which reduces the Tx duty cycle compared to TSCH. However, in the case of RT-RBO-TSCH, some parts of nodes in the network partially use RBO-TSCH operation, and another part operates with zero or small size of RBO SET. As a result, the Tx radio duty cycle of RT-RBO-TSCH is higher than RBO-TSCH and lower than TSCH.

In the Rx radio duty cycle graph, when traffic load is higher, the Rx duty cycle of TSCH increases dramatically. As average IPI decreases, the link reliability of TSCH



(a) Tx radio duty cycle

(b) Rx radio duty cycle

Figure 5.3: The evaluation of radio duty cycle.

drops rapidly. For this reason, there are many nodes that experience the TSCH network leaving and re-joining. After experiencing the TSCH network leaving, a node has to turn on the radio as always-on for listening to the enhanced beacon (EB) to re-join the TSCH network. As a result, TSCH consumes more energy than RBO-TSCH. However, when traffic load is lower, RBO-TSCH consumes more energy since it turns on the radio longer than TSCH to receive the packet applied to random back-off. On the other hand, RT-RBO-TSCH can reduce the duty cycle of RBO-TSCH in all traffic situations since it can change the size of RBO SET according to detecting collision and considering collision history. All the leaf nodes in RT-RBO-TSCH cannot receive any packets from their child nodes, so they act as TSCH in RT-RBO-TSCH. This operation is a dominant cause of reducing duty cycle of RBO-TSCH.

5.4 Network Stability

To evaluate network stability, we estimate average the number of leaving in the TSCH network and average the number of transmitted routing control messages and routing path change. In the link layer, the number of leaving represents synchronization broken between the Tx-Rx pair. They maintain synchronization by exchanging keep-alive message and timing information in unicast message ACK. If the network becomes unstable, the node cannot fit the synchronization with their timesource. For this reason, the node leaves the TSCH network. In the routing layer, we use the routing protocol for low-power and lossy networks (RPL) [9]. In RPL, if the network becomes unstable, the node frequently changes its routing path to find optimal link reliability path and transmits the RPL control message to announce the instability of the network. To this end, we estimate several metrics to verify the network stability in TSCH, RBO-TSCH, and RT-RBO-TSCH.

Figure 5.4 represents network stability in the link layer. In the case of TSCH, as the traffic load is augmented, leaving the TSCH network occurs in IPI of 8 seconds.

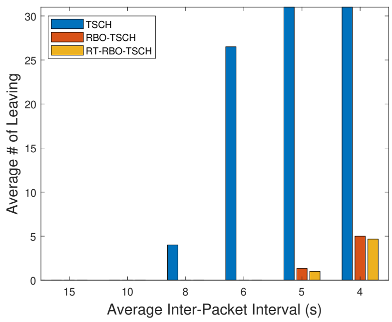
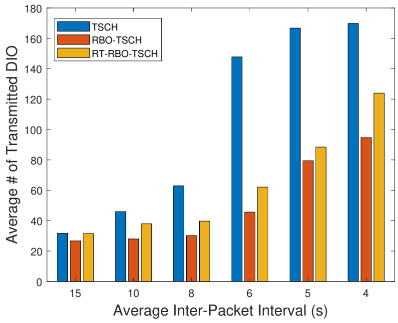


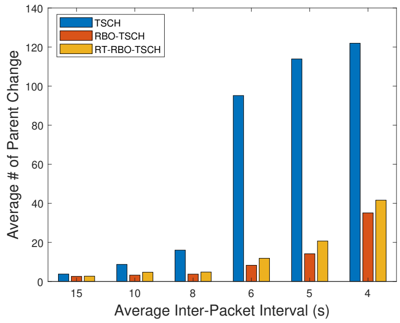
Figure 5.4: The evaluation of link layer stability.

Over IPI of 6 seconds, leaving the TSCH network occurs in all the nodes. However, the first case of leaving the TSCH network in RBO-TSCH and RT-RBO-TSCH occurs in IPI of 5 seconds. This means that RBO-TSCH and RT-RBO-TSCH can exchange the keep-alive message and unicast message better since they have higher reliability than TSCH. Also, in higher traffic, RBO-TSCH and RT-RBO-TSCH have a smaller number of leaving TSCH network than TSCH, which represents that they are more robust than TSCH.

In Figure 5.5, both graphs show the network stability in the routing layer. As the traffic is augmented, all the nodes in the network frequently change the routing path to find an optimal path and transmit the RPL control message such as destination-oriented directed acyclic (DODAG) information object (DIO) to announce the network inconsistency. When traffic load is higher, two metrics in TSCH increases dramatically. The reasons are **(1)** the routing layer is affected by the link layer, **(2)** TSCH cannot overcome the traffic over IPI of 6 seconds. However, RBO-TSCH and RT-RBO-TSCH are more robust than TSCH even though they also increase slightly as the traffic is higher.



(a) Network stability



(b) Routing path stability

Figure 5.5: The evaluation of routing layer stability.

Chapter 6

Conclusion

6.1 Conclusion

In this paper, we verified the collision occurred due to the inefficiency of using CCA operation in TSCH and proposed the RBO-TSCH to mitigate the collision by using the random back-off within timeslot operation. RBO-TSCH always outperforms than TSCH in reliability, however, the duty cycle is higher than TSCH in lower-traffic situations. Therefore, we also designed the *receiver-triggered* RBO-TSCH which can adaptively control the size of RBO SET in the receiver side by estimating the presence of the collision. To verify the performance of *receiver-triggered* RBO-TSCH and RBO-TSCH compared to TSCH, we implemented these on a low-power embedded device using Contiki OS. We evaluated it in IoT-LAB which is located in Strasbourg, France. Consequently, we have shown that *receiver-triggered* RBO-TSCH has higher reliability than TSCH. In the duty cycle, *receiver-triggered* RBO-TSCH can reduce the energy consumption of RBO-TSCH when the traffic is lower, and it has always lower duty cycles than TSCH and RBO-TSCH in higher traffic. As future work, we plan to not only design a method for elaborate collision detection in the receiver side but also consider the *receiver-triggered* RBO-TSCH from the perspective of channel hopping.

Bibliography

[1] J. Adkins, B. Ghena, N. Jackson, P. Pannuto, S. Rohrer, B. Campbell, and P. Dutta, "The signpost platform for city-scale sensing," in *2018 17th ACM/IEEE International Conference on Information Processing in Sensor Networks (IPSN)*. IEEE, 2018, pp. 188–199.

[2] H.-S. Kim, J. Ko, and S. Bahk, "Smarter markets for smarter life: applications, challenges, and deployment experiences," *IEEE Communications Magazine*, vol. 55, no. 5, pp. 34–41, 2017.

[3] J. Ko, C. Lu, M. B. Srivastava, J. A. Stankovic, A. Terzis, and M. Welsh, "Wireless sensor networks for healthcare," *Proceedings of the IEEE*, vol. 98, no. 11, pp. 1947–1960, 2010.

[4] C. Adjih, E. Baccelli, E. Fleury, G. Harter, N. Mitton, T. Noel, R. Pissard-Gibollet, F. Saint-Marcel, G. Schreiner, J. Vandaele *et al.*, "Fit iot-lab: A large scale open experimental iot testbed," in *2015 IEEE 2nd World Forum on Internet of Things (WF-IoT)*. IEEE, 2015, pp. 459–464.

[5] "Ieee standard for low-rate wireless networks," *IEEE Std 802.15.4-2015 (Revision of IEEE Std 802.15.4-2011)*, pp. 1–709, 2016.

[6] J. Polastre, J. Hill, and D. Culler, "Versatile low power media access for wireless sensor networks," in *Proceedings of the 2nd international conference on Embedded networked sensor systems*, 2004, pp. 95–107.

[7] M. Buettner, G. V. Yee, E. Anderson, and R. Han, "X-mac: a short preamble mac protocol for duty-cycled wireless sensor networks," in *Proceedings of the 4th international conference on Embedded networked sensor systems*, 2006, pp. 307–320.

[8] Y. Sun, O. Gurewitz, and D. B. Johnson, "Ri-mac: a receiver-initiated asynchronous duty cycle mac protocol for dynamic traffic loads in wireless sensor networks," in *Proceedings of the 6th ACM conference on Embedded network sensor systems*, 2008, pp. 1–14.

[9] T. Winter, P. Thubert, A. Brandt, J. W. Hui, R. Kelsey, P. Levis, K. Pister, R. Struik, J.-P. Vasseur, R. K. Alexander *et al.*, "Rpl: Ipv6 routing protocol for low-power and lossy networks." *rfc*, vol. 6550, pp. 1–157, 2012.

[10] S. Duquennoy, B. Al Nahas, O. Landsiedel, and T. Watteyne, "Orchestra: Robust mesh networks through autonomously scheduled tsch," in *Proceedings of the 13th ACM conference on embedded networked sensor systems*, 2015, pp. 337–350.

초 록

최근 사물 인터넷(Internet of Things) 시장의 발전이 급성장함에 따라 저 전력 무선 센서 네트워크에 초점을 맞춘 연구가 활발히 진행되고 있다. 특히, IoT의 요구조건을 만족하기 위해 높은 신뢰도와 저 전력의 특징을 가지는 IEEE 802.15.4 TSCH (Time-Slotted Channel Hopping) 기반의 네트워크를 사용한 연구가 많이 이루어 지고 있다. TSCH를 사용하는 송신자와 수신자는 timeslot을 이용한 시간 동기화된 통신을 통하여 데이터를 교환한다. 그러나 TSCH 네트워크의 같은 timeslot과 채널에서 다자 간 전송이 일어나게 될 경우, 심각한 데이터 충돌이 발생하게 된다. 이에 따라, 본 논문에서는 timeslot 내에서 랜덤하게 back-off를 진행 후 전송하게 함으로써 충돌을 회피할 수 있게 하는 Random Back-Off TSCH (RBO-TSCH)를 제안하였다. 더하여, RBO-TSCH의 에너지 소비를 줄이기 위해 송신자가 랜덤 back-off set의 개수를 적응적으로 제어하는 *receiver-triggered* RBO-TSCH를 제안하였다. 이를 검증하기 위해, 여러 실험들을 수행하였으며, RBO-TSCH와 *receiver-triggered* RBO-TSCH를 평가하였다. TSCH와 비교하여, 두 기법이 최대 3.8배 높은 신뢰성을 가지며, 링크 계층과 라우팅 계층에서 모두 충돌에 대하여 더 높은 안정성을 가진다는 것을 증명하였다.

주요어: IEEE 802.15.4, TSCH, 무작위 백오프 (Random Back-Off), CCA, 무선 네트워크 (Wireless Networks)

학 번: 2018-25692